63-3-5



NRL Report 5896

# THE PRIMARY COSMIC RADIATION

M. M. Shapiro

Cosmic Rays Branch
Nucleonics Division

and

Weizmann Institute of Science

April 25, 1963

U. S. NAVAL RESEARCH LABORATORY
Washington, D.C.

## ABSTRACT

This lecture sketches some salient features of the cosmic radiation incident upon the earth and discusses implications of the Li-Be-B anomaly and the helium isotope abundances.

The abundance ratio of cosmic-ray hydrogen to helium is similar to that for the thermal abundances in the sun and nearby stars. The other nuclei, particularly Li, Be, and B, are overabundant relative to hydrogen. Lower limits of cosmic-ray-particle flux and density for total energies exceeding $1.7 \times 10^9$ ev per nucleon are 0.28 particle/cm$^2$-sec-sterad and $1.2 \times 10^{-10}$/cm$^3$, respectively. The energy density is comparable to that of starlight. Over a wide range of energies, the energy spectrum conforms to a power law in W, the total energy per nucleon: the intergral directional intensity varies as $W^{-1.5}$. Above $10^{14}$ ev, the spectrum appears steeper, but its exact shape is as yet uncertain. The largest air shower reported came from a particle of an estimated $6 \times 10^{19}$ ev. For a galactic magnetic field of $3 \times 10^{-6}$ gauss, such particles would escape from the galaxy.

NRL measurements indicate that the cosmic-ray abundance of Li, Be, and B at kinetic energies above $1.5 \times 10^9$ ev/nucleon is $2 \times 10^5$ times their general abundance. An assumption that this overabundance arises from the breakup of heavier nuclei permits estimates of the amount of interstellar hydrogen traversed, one estimate being 2.5 g/cm$^2$. The relative abundances of the helium isotopes are being investigated as a further means of calculating cosmic-ray path lengths.

## AUTHORIZATION

NRL Problem H01-07
Project RR-002-06-41-5004

Manuscript submitted December 3, 1962.

# THE PRIMARY COSMIC RADIATION

M. M. Shapiro
Nucleonics Division, U.S. Naval Research Laboratory, Washington, D.C.,
and
Weizmann Institute of Science, Rehovoth, Israel*

## INTRODUCTION

The galaxy may be considered as a quasi-stationary reservoir of magnetically confined cosmic rays randomized in direction by turbulent clouds of plasma. Information about the galactic radiation comes not only from cosmic-ray experiments per se, but also from radio-astronomical observations. The former are carried out mainly with large balloons near the top of the atmosphere; however, satellites and space probes have begun to play an important role. In addition, much effort is being devoted to studies of extensive air showers deep in the atmosphere. As for the radio-astronomical evidence about cosmic rays in remote regions of the galaxy, this will be treated in the following lecture on cosmic-ray origin.†

In this lecture we shall sketch come salient features of the cosmic radiation incident upon the earth, e.g., its composition, energy, and isotropy. Then we shall discuss implications of the Li-Be-B anomaly and the helium isotope abundances.

## SOME SALIENT FEATURES OF THE COSMIC RADIATION

### Composition

Of the various primary components, only the nuclear component is well established. Table 1 gives the relative abundances of the atoms at thermal energies and at cosmic-ray energies. It can be seen that the ratio of cosmic-ray hydrogen to helium is similar to that for the thermal abundances of these elements in the sun and nearby stars. All the cosmic-ray nuclei heavier than helium comprise less than 2 percent of the total, but their relative abundance is nevertheless notably higher than that of the same elements in the universal (i.e., thermal) distribution. Table 2 lists abundances for the groups of nuclei above helium. The "light" group—Li, Be, and B—is enormously overabundant relative to hydrogen; the implications of this anomaly are discussed in the second half of this lecture. The medium, heavy, and "very heavy" components are more moderately, but progressively overabundant. A possible explanation for this will be discussed in the next lecture, on cosmic-ray origin.

A further breakdown of the relative abundances for the individual light and medium elements is provided in Table 3, which shows the results of the NRL group in Washington and those of other workers. A noteworthy feature of the cosmic-ray distribution is that carbon is more abundant than oxygen, whereas the reverse is true of the thermal distribution of these elements.

*Guggenheim Fellow and visiting professor of physics at the Weizmann Institute in 1962-63.
†This is the first of two lectures presented at the Enrico Fermi International School of Physics course on Stellar Evolution, in Varenna, Italy, August 1962. The second lecture is "Origin of Cosmic Rays in Supernovae and Other Sources," printed as NRL Report 5951, May 1963.

Table 1
Relative Abundances of the Atoms at Thermal Energies and Cosmic-Ray Energies

| Element | "General" (i.e., thermal) Abundance* (%) | Cosmic-Ray Abundance | | |
|---|---|---|---|---|
| | | At Comparable Energies per Nucleon (%) | At Comparable Magnetic Rigidities† (%) | Absol. Flux (peters‡) |
| Hydrogen | 86.6 | 94 | 86 | 600 ± 30 |
| Helium | 13.3 | 5.5 | 13 | 89 ± 3 |
| Elements with Z ≥ 3 | 0.14 | 0.6 | 1.4 | 10.1 ± 0.4 |

*According to Cameron's revision of the table of abundances by Suess and Urey.
†Exceeding 4.5 GV, i.e., at geomagnetic latitude 41°N (Texas).
‡Peters = particles/$m^2$-sec-ster.

Table 2
Abundances of the Elements Relative to $10^5$ Hydrogen Atoms

| Element | Universal (thermal) Abundance* | Cosmic-Ray Abundance† | Ratio of Cosmic-Ray to Thermal Abundances |
|---|---|---|---|
| Hydrogen | $10^5$ | $10^5$ | 11 |
| L-group (Li, Be, B) | $5 \times 10^{-4}$ | 110 | $\sim 2 \times 10^5$ |
| M-group (C, N, O, F) | 150 | 400 | ~3 |
| H-group (Z ≥ 10) | 15 | 150 | ~10 |
| V.H. (Z ≥ 20)‡ | 0.7 | 40 | ~60 |

*Cameron's revision of the Suess and Urey data is employed here for the general (i.e., thermal) abundances.
†The cosmic-ray abundances refer to the same <u>energy</u> threshold (kinetic energy E > 1.5 Bev/nucleon).
‡The very heavy (V.H.) component is a subgroup of the heavy (H) component.

Studies of the isotopic abundances in the cosmic radiation have just begun, and early results for the helium isotopes are discussed in the second half of this lecture.

Our knowledge of primaries other than nuclei is rudimentary. There is evidence for the arrival of primary electrons in numbers small (about 3 percent) compared to those of protons (Earl, and Meyer and Vogt).* An MIT satellite experiment has detected gamma rays with energies above 50 Mev (Clark and Kraushaar). The collaborative BASJE air shower array on Mt. Chacaltaya in Bolivia has apparently detected primary gamma rays with energies above $10^{14}$ ev. In addition, experiments are currently designed or under way to detect primary neutrinos and positrons, as well as fast solar neutrons.

Table 3
Relative Abundances
of the Elements ($Z \geq 3$) in the Primary Cosmic Radiation*

| Relative to All Nuclei ($Z \geq 3$) (%) | | Z | Relative to Carbon (%) | |
|---|---|---|---|---|
| NRL | Others | | NRL | Others |
| 5.3 | 5.2 | 3 | 17.6 | 21.4 |
| 2.3 | 4.3 | 4 | 7.6 | 17.1 |
| 7.4 | 11.9 | 5 | 24.6 | 47.4 |
| 30.1 | 25.1 | 6 | 100.0 | 100.0 |
| 9.7 | 14.9 | 7 | 32.2 | 59.3 |
| 19.4 | 14.5 | 8 | 64.4 | 57.8 |
| 2.4 | 4.0 | 9 | 8.0 | 15.9 |
| 15.0 | 21.4 | L | 49.8 | 85.2 |
| 61.6 | 58.5 | M | 205.0 | 233.0 |
| 23.4 | 20.1 | H | 77.7 | 80.0 |

*After O'Dell, Shapiro, and Stiller.

## Particle Flux and Density in the Vicinity of the Earth, Outside the Magnetosphere

Let W = total energy per nucleon
= (kinetic energy E + rest mass energy)/nucleon.

Furthermore, let us adopt an arbitrary threshold energy $W_0 = 1.7$ Gev (corresponding to a mean energy $\bar{W}$ of 5 Gev). Then the following are, respectively, the integral directional intensity $J_{>W_0}$ and the particle density $n_{>W_0}$ at energies exceeding $W_0$:

$$J_{>W_0} = 0.28 \text{ particle/cm}^2\text{-sec-sterad}$$
$$n_{>W_0} = 1.2 \times 10^{-10}/\text{cm}^3.$$

These numbers may be considered as lower limits to the total directional flux and particle density at times of low solar activity in the 11-year cycle.

## Energy Spectra of Primary Cosmic-Ray Nuclei

At kinetic energies of the order of $10^8$ ev the spectrum has a peak whose position and magnitude vary with solar activity.

Over the wide energy interval

$$2.5 \times 10^9 < W < 10^{14} \text{ ev/nucleon},$$

the directional intensity of particles with energy exceeding W is expressible as a simple power of the total energy per nucleon:

$$J_{>W} \propto W^{-1.5}.$$

*See the first item in the bibliography.

Within experimental error, the same exponent, -1.5, fits the spectra of hydrogen, helium, and the heavier nuclei. Line segment AB in Fig. 1 indicates the range over which this exponent applies.

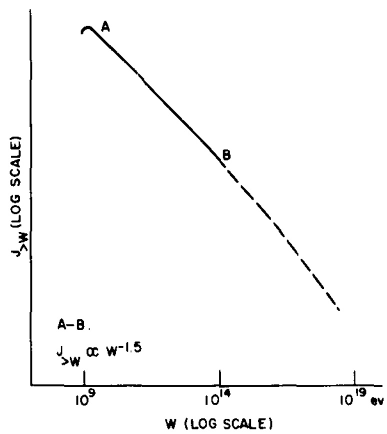


Fig. 1 - A schematic energy spectrum of primary cosmic-ray nuclei. W is the total energy per nucleon.

Above $10^{14}$ ev, it was formerly thought that the spectrum falls off more sharply (approximately as $W^{-2.2}$), but some recent data give an exponent of $-1.8 \pm 0.3$ even above $10^{15}$ ev. This suggests that a single power spectrum may be valid up to very high energies.

In the energy interval from $10^{12}$ ev up to nearly $10^{15}$ ev, information can be obtained from the nuclear interactions ("jets") observed in huge, balloon-borne stacks of nuclear emulsion. Extensive data on these jets have recently begun to emerge from the International Cooperative Emulsion Flights (ICEF project) organized by the University of Chicago. At energies above $10^{15}$ ev, extensive air showers detected at mountain altitudes, at sea level, and underground reveal the incidence of ultra-high-energy particles. Versatile arrays of detectors, including scintillation counters, Cerenkov counters, neutron piles, and multiplate cloud chambers, as well as ordinary Geiger counters, are used. The largest single shower thus far reported (by the MIT group) was estimated to have been initiated by a particle of $6 \times 10^{19}$ ev.

As mentioned above, the <u>mean</u> energy per nucleon for the arbitrary threshold $W_0$ taken above is

$$\overline{W} = 5 \times 10^9 \text{ ev/nucleon.}$$

The flux of nucleons $F_{>W_0}$ is 0.36/cm$^2$ sec sterad, so the energy flux $\phi$ is given by

$$\phi = F_{>W_0}\ \overline{W} = 0.36 \times 5 \times 10^9 = 1.8 \times 10^9 \text{ ev/cm}^2\text{-sec-sterad.}$$

The energy density, for particles moving with the velocity of light c is given by

$$\frac{4\pi}{c}\,\phi = 0.75 \text{ ev/cm}^3.$$

This is a lower limit, and its magnitude is roughly the same as the energy density of starlight.

### Magnetic Confinement

At energies exceeding several Gev/nucleon, the energy $E_n$ of an ion moving in a magnetic field is related to the charge, the magnetic field, and the radius of the helix it describes by

$$E_n = 300\ Z\ H\ r = A\ E$$

if E, the kinetic energy per nucleon, is expressed in ev, H in gauss, and r in centimeters; A is the mass number.

It is instructive to tabulate r for several high energies of protons and ironlike nuclei. As a representative value of the magnetic field strength in the galaxy, we have taken $H = 3 \times 10^{-6}$ gauss. In Table 4 the radii are given in light years for ions of energy $10^{12}$, $10^{16}$, and $10^{20}$ ev. The last column of this table shows that, for the assumed value of H, protons of $10^{20}$ ev would not be confined in the galaxy. Even iron nuclei having the same energy $E_n$ would have a good chance to escape before being destroyed by collision, for in traversing $10^6$ light years, they would be penetrating less than 1 g/cm² of interstellar material. We have tacitly assumed that the galactic halo, as well as the disk, serves as a trapping region. If this were not the case, then particles having energies lower than $10^{20}$ ev would also escape. Some evidence has been found (Linsley and Scarsi) that the highest energy cosmic rays are protons. This suggests that they are extragalactic in origin.

### Isotropy

Above $10^{10}$ ev the incidence of cosmic rays upon the earth's magnetosphere is nearly isotropic. This implies strong stirring by magnetic fields in the galaxy. One might expect some anisotropy at the very highest energies, and this question has been explored with arrays of extensive air shower detectors that reveal directions of arrival. At the Kyoto Conference on Cosmic Rays in 1961, evidence for some anisotropy was presented by the groups from Tokyo, Cornell, and MIT. After acquiring further data, however, the MIT group no longer found a directional effect (Latin-American Symposium on Cosmic Radiation, La Paz, Bolivia, 1962).

Table 4
Radii of Helices
Described by Ultra-High-Energy
Nuclei of Z = 1 and Z = 25 in a
Magnetic Field of $3 \times 10^{-6}$ Gauss

| $E_n = AE$ | Radius (light years*) | | |
|---|---|---|---|
| | $10^{12}$ ev | $10^{16}$ ev | $10^{20}$ ev |
| Z = 1 | $10^{-3}$ | 10 | $10^{5}$ |
| Z = 25 | $4 \times 10^{-5}$ | 0.4 | 4,000 |

*1 lt yr = $0.95 \times 10^{18}$ cm.

## IMPLICATIONS OF THE Li-Be-B ANOMALY AND THE HELIUM ISOTOPE ABUNDANCES

### The Relative Abundances of Primary Li, Be, and B

The universal abundance of the three light elements Li, Be, and B is known to be exceedingly low—several atoms per $10^9$ hydrogen atoms. In the decade of the 1950's there was a prolonged controversy over the questions: (a) does the primary cosmic radiation contain an appreciable fraction of these light elements? and (b) if so, what is the magnitude of this fraction? These questions have an important bearing on the "age" of the radiation and on its propagation through interstellar space, since the Li, Be, and B could arise from the collision and breakup of heavier cosmic-ray nuclei. Then the relative intensity of such secondary light nuclei at the top of the earth's atmosphere would depend upon the average number of collisions suffered by the primordial nuclei, and hence upon the average amount of material they had traversed. Thus, reasonable estimates of the mean path length of cosmic-ray nuclei in the galaxy, from their sources to the earth, can be deduced from the abundance of the light element group.

In balloon flight experiments using mainly nuclear emulsion as detectors, various investigators have reported conflicting intensities for the Li-Be-B group, ranging all the way from zero to fluxes approaching those of the heavier atoms. A major difficulty has been that the residual air above the balloon generates secondary light nuclei from the collision breakup of heavier ones. So these secondaries must be separated from the true primaries. The identification of a fast nucleus–i.e., the correct determination of its charge–has also posed experimental difficulties, and the low absolute flux of nuclei heavier than helium has placed severe limitations on the statistical weight of many of the experiments.

At the U.S. Naval Research Laboratory (NRL), O'Dell, Shapiro, and Stiller were fortunate in getting an emulsion stack exposure at an atmospheric depth of only 2.7 $g/cm^2$. This made the process of extrapolation to the top of the atmosphere much less uncertain than heretofore. Moreover, they gathered an adequate statistical sample, nearly 1000 tracks of cosmic-ray nuclei heavier than helium. Finally, they designed the experiment to meet the problem of charge resolution by employing several independent methods of ionization measurement. Their stack included emulsions of different sensitivities, and a single cosmic-ray nucleus usually passed through several different types of emulsion, leaving tracks of different densities in each. It was thus possible to compare the apparent charge of a cosmic-ray nucleus deduced from the track it left in one emulsion with that in another.

The resulting resolution between individual elements in the light and medium groups was good, and, in particular, clean separation was achieved between the crucial elements boron and carbon, segregating the light group of nuclei from all the heavier ones. The relative abundances observed in the emulsion were corrected for the secondaries produced during the ascent of the balloon, and for those produced at altitude in the overlying material, and especially in the residual air. By using appropriate diffusion equations, the ratio of the light elements Li, Be, and B to all heavier ones at the top of the atmosphere was found to be $0.18 \pm 0.04$. From this it was concluded that the primary cosmic-ray abundance of these light elements relative to hydrogen at kinetic energies above 1.5 Gev/nucleon, is approximately $2 \times 10^5$ times as great as their relative universal abundance.

Other results on the chemical composition of the primary radiation are shown in Table 3.

Next we examine what can be learned from the abundances of the light elements about the average amount of interstellar material traversed by the heavier cosmic-ray nuclei. This material consists mainly of hydrogen, at a density that is not well known. Within the galactic disk, the average density is assumed to be of the order of 1 $atom/cm^3$, and in the galactic halo it is lower by perhaps two orders of magnitude. To determine what happens when the heavy nuclei collide with hydrogen, one needs the partial cross sections for the different types of breakup of the various nuclei at cosmic-ray energies. Some experimental information is available, mainly for the inverse process–the collision of fast protons with other target nuclei, but there is a dearth even of such data.

Recently, Daniel and collaborators at the Tata Institute have calculated the partial cross sections for the production of many nuclides by breakup in hydrogen. They found good agreement between the calculated values and those experimentally available for a limited number of isotopes. The Bombay group then used the NRL experimental results on the relative abundances of light and heavier nuclei at the top of the atmosphere to deduce the amount of interstellar hydrogen traversed, and they thus obtained a mean path length of $2.5 \pm 0.5$ $g/cm^2$.

Isotopic Composition of Cosmic-Ray Helium

The universal, i.e., thermal, abundance of $He^3$ appears to be very low compared with that of $He^4$ on the earth and in the sun's envelope. Insofar as is known–and information is admittedly meager–the same is true of most stars. There is, in fact, only one well authenticated case of a star having a high abundance of $He^3$, i.e., 3 Centauri A, in which the isotopic shifts in wavelength of the helium-I lines suggest that 75 to 95 percent of all the helium in the stellar envelope consists of $He^3$. This very exceptional star has been discussed in the lecture by Dr. E. M. Burbidge.

It is of great interest to ascertain the isotopic composition of primary cosmic-ray helium. If an appreciable flux of $He^3$ is present, and if it arises mainly as a fragmentation product, then this provides an independent method for estimating the mean path length traversed in space by the primordial radiation. Although $He^3$ could arise as a breakup product of elements heavier than helium, the main contribution would come from the stripping of $He^4$ to give mass-3 particles. We must take into account not only the $He^3$ generated directly in this way, but also the tritium so produced; for the latter decays into $He^3$ with a lifetime of about 12 years, and it would therefore be completely converted to $He^3$ during the long transit time.

The first experiments aimed at measuring the relative abundances of the helium isotopes in the primary radiation were carried out by M.V.K. Appa Rao. At energies of about 200-300 Mev/nucleon, he measured the multiple coulomb scattering along helium tracks as a function of range, and reported values ranging from 0.31 to 0.41 for the ratio $He^3/(He^3 + He^4)$. These values represent rather large fluxes of $He^3$, and if the latter is produced entirely by spallation of $He^4$ or heavier nuclei, then the experimental results would imply passage through 12-14 $g/cm^2$ of interstellar material.

Last year the NRL group (Hildebrand, O'Dell, Shapiro, Silberberg, and Stiller) undertook a balloon-borne experiment designed to resolve $He^3$ from $He^4$ by two independent methods. A 2.8-liter stack of Ilford K.2 stripped emulsion was flown April 21, 1961, at geomagnetic latitude 55°N for 11.2 hours at a mean atmospheric depth of 3.8 $g/cm^2$. The relative insensitivity of the K.2 emulsion made it possible to deduce the rate of ionization loss from grain counting. Mass identification was accomplished by measuring ionization versus range and multiple scattering versus range (constant sagitta technique). Preliminary data based on 83 tracks suggest that the ratio $He^3/(He^3 + He^4)$ is of the order of 0.1, and is unlikely to exceed 0.2. This provisional result should be treated with reserve, not only in view of the limited statistics, but also because, thus far, the ionization method and the scattering method have not yet agreed sufficiently to yield a reliable value.

There are several effects that can produce a low-mass tail in the distribution of $He^4$ alone, i.e., there are several ways in which a $He^4$ track can spuriously resemble $He^3$. So it is perhaps noteworthy that the scattering method at NRL, employing some 600 scattering cells per track, has thus far yielded a negligible $He^3$ abundance, unlike the ionization-range data. We conclude that the identification of isotopic mass by a single method demands a precise knowledge of the resolution function involved. By correlating two independent methods, it may be expected that the uncertainty in the isotopic analysis of helium can be reduced.

Let us assume that $He^3$ is present in the primary cosmic radiation reaching the earth, and that it arises from $He^4$ stripping by interstellar hydrogen. Then we can estimate the thickness of hydrogen traversed with the help of cross-section data from experiments on a (nearly) inverse reaction. Innes bombarded helium with 300-Mev neutrons, and obtained a total cross section of $10^{-25}$ $cm^2$, corresponding to an interaction mean free path of 16.7 $g/cm^2$. In 42 percent of the collisions, a mass-3 particle was produced. Thus the mean free path for conversion of mass-4 to mass-3 is about 40 $g/cm^2$. Using this value, and

introducing a correction for the production of $He^3$ from heavier elements, we find that, starting with primordial cosmic rays devoid of $He^3$, a fraction of about 10 percent $He^3$ is produced after passage through about 4 $g/cm^2$ of hydrogen. Calculations by Hayakawa and by Appa Rao yield a similar result, that a relative abundance of 0.1 implies passage through about 3 $g/cm^2$ of hydrogen. On the other hand, the isotopic ratio of 0.3 to 0.4 obtained by Appa Rao implies passage through some 13 $g/cm^2$.

Now, this long path differs markedly from the path deduced from the NRL result on the elements Li, Be, and B. Those results were, however, obtained for nuclei with energies above 1.5 Gev/nucleon. Hence a large $He^3$ flux might be reconcilable with the observed abundance of the light elements if, for some reason, slow cosmic rays travel over a longer path length from their sources to the earth than higher energy cosmic rays. This explanation is apparently contradicted by recent results of the Rochester group on deuterium at energies comparable to those in the helium investigations. They placed a very low upper limit on the abundance of this nuclide in the cosmic rays. Yet, if we are to interpret a high abundance of slow $He^3$ in terms of a long path length, then we should expect to find a considerable flux of deuterium as well. Thus, if Appa Rao's results should be confirmed, then it may be necessary to conclude that most of the $He^3$ is not secondary in origin but that it originates as such in cosmic-ray sources. It is plain that much additional experimental work on isotopic composition will be required to resolve the present conflicts.

# BIBLIOGRAPHY

The Best Single Current Source on Recent Cosmic-Ray Research:

Proc. Kyoto Conference on Cosmic Rays, 1961, J. Phys. Soc. Japan, Vol. 17; see especially Supplement A-III, 1962. References in the present text not otherwise listed in this bibliography will be found in the Proceedings.

On the General, i.e., Thermal Abundances of the Elements:

H.E. Suess and H.C. Urey, Handbuch d. Physik, Vol. 51, Berlin:Springer, 1958, p. 296; Rev. Mod. Phys. 28:53 (1956)

A.G.W. Cameron, Astrophys. J. 129:676 (1959)

L.H. Aller, "The Abundance of the Elements," New York:Interscience, 1961

On Li, Be, and B in the Primary Cosmic Radiation:

F.W. O'Dell, M.M. Shapiro, and B. Stiller, Internat. Conf. on Cosmic Radiation (IUPAP), Kyoto, Sept. 1961, J. Phys. Soc. Japan 17(Suppl. A-III):23 (1962)

G.D. Badhwar, R.R. Daniel, and B. Vijayalakshmi, Tata Inst. of Fundamental Research, Bombay (private communication from Dr. Daniel)

On the Helium Isotopes:

M.V.K. Appa Rao, Phys. Rev. 123:295 (1961); also, Univ. of Rochester Report No. NYO-10029, Nov. 1961, submitted to J. Geophys. Research

M. Shapiro, B. Hildebrand, F.W. O'Dell, R. Silberberg, and B. Stiller, "Transformations of Complex Cosmic-Ray Nuclei in Galactic Space," Proc. of Internat. Space Symposium (COSPAR), Washington, D.C., May 1962 (in press)

H. Innes, thesis, UCRL Report 8040, Univ. of California, 1957

On the Primary Cosmic Radiation:

C.J. Waddington, Prog. in Nuclear Phys. 8:1 (1960)

M.M. Shapiro, Trans. N.Y. Acad. Sci. 20:697 (1958)

Hand. d. Physik (Encyclopedia of Physics), "Cosmic Rays 1," Vol. 46/1, ed. S. Flügge, Berlin:Springer-Verlag, 1961

UNCLASSIFIED

Naval Research Laboratory. Report 5896. THE PRIMARY COSMIC RADIATION, by M.M. Shapiro. 9 pp. and fig., April 25, 1963.

1. Cosmic rays

I. Shapiro, M. M.

This lecture sketches some salient features of the cosmic radiation incident upon the earth and discusses implications of the Li-Be-B anomaly and the helium isotope abundances.

The abundance ratio of cosmic-ray hydrogen to helium is similar to that for the thermal abundances in the sun and nearby stars. The other nuclei, particularly Li, Be, and B, are overabundant relative to hydrogen. Lower limits of cosmic-ray-particle flux and density for total energies exceeding $1.7 \times 10^9$ ev per nucleon are 0.28 particle/cm$^2$-sec-sterad and

UNCLASSIFIED (over)

UNCLASSIFIED

Naval Research Laboratory. Report 5896. THE PRIMARY COSMIC RADIATION, by M.M. Shapiro. 9 pp. and fig., April 25, 1963.

1. Cosmic rays

I. Shapiro, M. M.

This lecture sketches some salient features of the cosmic radiation incident upon the earth and discusses implications of the Li-Be-B anomaly and the helium isotope abundances.

The abundance ratio of cosmic-ray hydrogen to helium is similar to that for the thermal abundances in the sun and nearby stars. The other nuclei, particularly Li, Be, and B, are overabundant relative to hydrogen. Lower limits of cosmic-ray-particle flux and density for total energies exceeding $1.7 \times 10^9$ ev per nucleon are 0.28 particle/cm$^2$-sec-sterad and

UNCLASSIFIED (over)

UNCLASSIFIED

Naval Research Laboratory. Report 5896. THE PRIMARY COSMIC RADIATION, by M.M. Shapiro. 9 pp. and fig., April 25, 1963.

1. Cosmic rays

I. Shapiro, M. M.

This lecture sketches some salient features of the cosmic radiation incident upon the earth and discusses implications of the Li-Be-B anomaly and the helium isotope abundances.

The abundance ratio of cosmic-ray hydrogen to helium is similar to that for the thermal abundances in the sun and nearby stars. The other nuclei, particularly Li, Be, and B, are overabundant relative to hydrogen. Lower limits of cosmic-ray-particle flux and density for total energies exceeding $1.7 \times 10^9$ ev per nucleon are 0.28 particle/cm$^2$-sec-sterad and

UNCLASSIFIED (over)

UNCLASSIFIED

Naval Research Laboratory. Report 5896. THE PRIMARY COSMIC RADIATION, by M.M. Shapiro. 9 pp. and fig., April 25, 1963.

1. Cosmic rays

I. Shapiro, M. M.

This lecture sketches some salient features of the cosmic radiation incident upon the earth and discusses implications of the Li-Be-B anomaly and the helium isotope abundances.

The abundance ratio of cosmic-ray hydrogen to helium is similar to that for the thermal abundances in the sun and nearby stars. The other nuclei, particularly Li, Be, and B, are overabundant relative to hydrogen. Lower limits of cosmic-ray-particle flux and density for total energies exceeding $1.7 \times 10^9$ ev per nucleon are 0.28 particle/cm$^2$-sec-sterad and

UNCLASSIFIED (over)

UNCLASSIFIED

$1.2 \times 10^{-10}/cm^3$, respectively. The energy density is comparable to that of starlight. Over a wide range of energies, the energy spectrum conforms to a power law in W, the total energy per nucleon: the integral directional intensity varies as $W^{-1.5}$. Above $10^{14}$ ev, the spectrum appears steeper, but its exact shape is as yet uncertain. The largest air shower reported came from a particle of an estimated $6 \times 10^{19}$ ev. For a galactic magnetic field of $3 \times 10^{-6}$ gauss, such particles would escape from the galaxy.

NRL measurements indicate that the cosmic-ray abundance of Li, Be, and B at kinetic energies above $1.5 \times 10^9$ ev/nucleon is $2 \times 10^5$ times their general abundance. An assumption that this overabundance arises from the breakup of heavier nuclei permits estimates of the amount of interstellar hydrogen traversed, one estimate being 2.5 $g/cm^2$. The relative abundances of the helium isotopes are being investigated as a further means of calculating cosmic-ray path lengths.

UNCLASSIFIED

UNCLASSIFIED

$1.2 \times 10^{-10}/cm^3$, respectively. The energy density is comparable to that of starlight. Over a wide range of energies, the energy spectrum conforms to a power law in W, the total energy per nucleon: the integral directional intensity varies as $W^{-1.5}$. Above $10^{14}$ ev, the spectrum appears steeper, but its exact shape is as yet uncertain. The largest air shower reported came from a particle of an estimated $6 \times 10^{19}$ ev. For a galactic magnetic field of $3 \times 10^{-6}$ gauss, such particles would escape from the galaxy.

NRL measurements indicate that the cosmic-ray abundance of Li, Be, and B at kinetic energies above $1.5 \times 10^9$ ev/nucleon is $2 \times 10^5$ times their general abundance. An assumption that this overabundance arises from the breakup of heavier nuclei permits estimates of the amount of interstellar hydrogen traversed, one estimate being 2.5 $g/cm^2$. The relative abundances of the helium isotopes are being investigated as a further means of calculating cosmic-ray path lengths.

UNCLASSIFIED

UNCLASSIFIED

$1.2 \times 10^{-10}/cm^3$, respectively. The energy density is comparable to that of starlight. Over a wide range of energies, the energy spectrum conforms to a power law in W, the total energy per nucleon: the integral directional intensity varies as $W^{-1.5}$. Above $10^{14}$ ev, the spectrum appears steeper, but its exact shape is as yet uncertain. The largest air shower reported came from a particle of an estimated $6 \times 10^{19}$ ev. For a galactic magnetic field of $3 \times 10^{-6}$ gauss, such particles would escape from the galaxy.

NRL measurements indicate that the cosmic-ray abundance of Li, Be, and B at kinetic energies above $1.5 \times 10^9$ ev/nucleon is $2 \times 10^5$ times their general abundance. An assumption that this overabundance arises from the breakup of heavier nuclei permits estimates of the amount of interstellar hydrogen traversed, one estimate being 2.5 $g/cm^2$. The relative abundances of the helium isotopes are being investigated as a further means of calculating cosmic-ray path lengths.

UNCLASSIFIED

UNCLASSIFIED

$1.2 \times 10^{-10}/cm^3$, respectively. The energy density is comparable to that of starlight. Over a wide range of energies, the energy spectrum conforms to a power law in W, the total energy per nucleon: the integral directional intensity varies as $W^{-1.5}$. Above $10^{14}$ ev, the spectrum appears steeper, but its exact shape is as yet uncertain. The largest air shower reported came from a particle of an estimated $6 \times 10^{19}$ ev. For a galactic magnetic field of $3 \times 10^{-6}$ gauss, such particles would escape from the galaxy.

NRL measurements indicate that the cosmic-ray abundance of Li, Be, and B at kinetic energies above $1.5 \times 10^9$ ev/nucleon is $2 \times 10^5$ times their general abundance. An assumption that this overabundance arises from the breakup of heavier nuclei permits estimates of the amount of interstellar hydrogen traversed, one estimate being 2.5 $g/cm^2$. The relative abundances of the helium isotopes are being investigated as a further means of calculating cosmic-ray path lengths.

UNCLASSIFIED